

Laser-Induced Graphene Pressure Sensors Manufactured via Inkjet PCB Printer

Locally Producing Super-Sensitive and Cost-Effective Circular Diaphragm Pressure Gauges

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Abstract—This paper demonstrates two firsts for the fields of laser-induced graphene (LIG) sensors and printed electronics (PE): (1) a LIG Kapton circular diaphragm gauge pressure sensor with a multi-resistor network; (2) the wiring and encapsulation of said sensor, printed with conductive and dielectric inks (CI and DI) utilized by the BotFactory SV2 thermal Inkjet PCB printer. In addition, the PE tool allows for automated solder paste dispensing and the pick-and-place of electronic components to form complete functioning microsystems, consisting of microcontrollers, thin-film batteries, passive components, antennas, etc. These capabilities further enhance the prospect of LIG sensors by providing to them off-grid power, read-out circuitry, amplification, and simple wireless data transmission.

Keywords—Printed Electronics; Laser Induced Graphene (LIG); Pressure Sensors; Flexible Electronics

I. INTRODUCTION

Low-cost, flexible microsystems are an ideal solution for health and environmental monitoring. A significant challenge in flexible electronics is to realize sensing and computation capability diversity while maintaining rapid prototyping. PE can enable rapid prototyping of electronic components; however, PE have lacked a proven sensor mechanism for mechanical forces – it is challenging to make microelectromechanical systems (MEMS) sensors and transducers in flexible electronics, comparable with the performance of silicon-based MEMS. LIG provides a quick and easy way to fabricate complex graphene-like piezoresistive microstructures for applications such as strain and chemical sensing [1–4]. This work describes the design and fabrication of a novel LIG pressure sensor utilizing a membrane-based device, insulating and conducting features formed by inkjet deposition, and graphene-like sensing elements formed by the laser pyrolyzation of a flexible Polyimide (Kapton) substrate.

A. Current Diaphragm Pressure Sensors on the Market and in the Literature

A key component for mechanical sensing is a strain gauge. Several LIG strain gauges have been reported with exceptional

sensitivity [1,2,4]—some even approaching an order of magnitude greater than those of metal foil sensors (MFSs) [3]. Although some have been simulated [5], no PE fabricated LIG diaphragm gauge pressure sensors have been experimentally demonstrated or characterized. Our group has previously demonstrated chemical vapor deposition (CVD) graphene-based sensors and actuators, with high piezoresistive gauge-factor response and large mechanical actuation, leading us to use graphene-based sensors in our current device [6, 7].

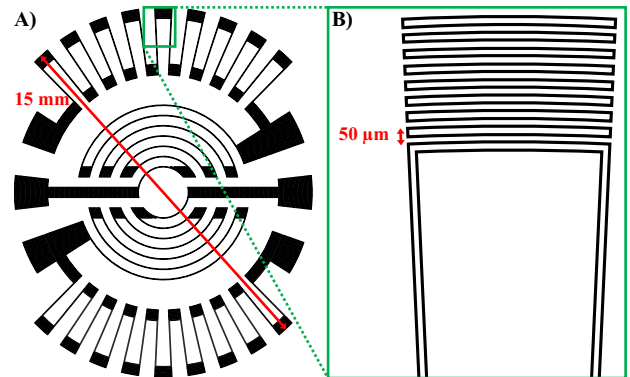


Fig. 1. A) Parametric CAD model of pattern to be laser hatched into Kapton film by the VLS3.60's laser beam which has a spot size of 25.4 μm . B) Magnification showing that hatch lines in this sketch are separated by 25 μm .

II. LIG-SENSORS WITH PE

Given its inherent pressure measurement versatility, a diaphragm type pressure sensor was determined to be the most desirable for this application. With a diaphragm-based sensor, the instrumented membrane side can be exposed, vacuum-sealed, or pneumatically connected by ports for measuring gauge, absolute, or differential pressures, respectively [9]. This work demonstrates an exposed-sensor for gauge measurements. Due to its radially symmetric stress distributions, a circular—rather than the more common rectangular—type diaphragm was chosen [8].

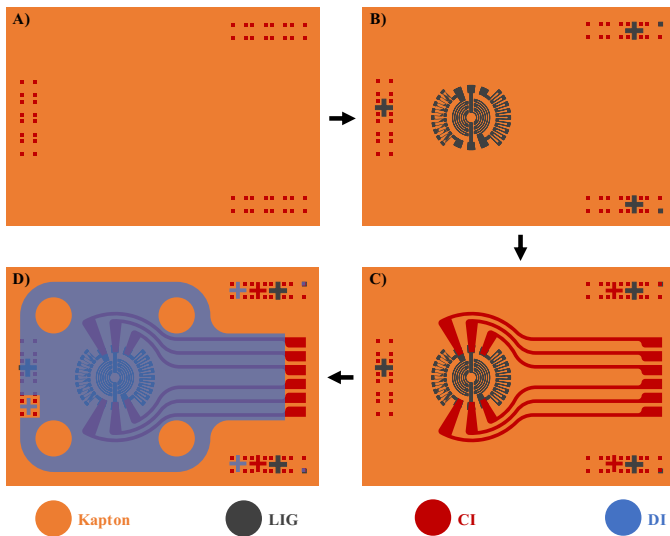


Fig. 2. Inkjet/Laser Process Flow: (A) BotFactory SV2 inkjet-printed conductive ink (CI) alignment marks on the Kapton sheet. B) Define the piezoresistors using laser pyrolyzation, using the conductive ink alignment marks as reference. C) SV2 prints CI electrical traces to form interconnects and contacts to the LIG sensor. D) SV2 printed dielectric ink (DI) protection layer film for passivation and damage from external sources.

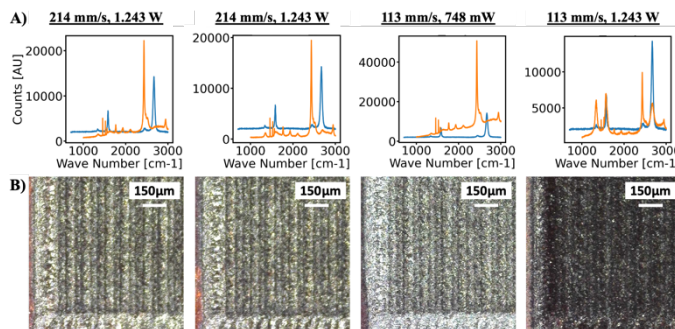


Fig. 3. A) Raman spectrums of the laser-induced graphene (orange) characterization patterns (LIGCPs) and high-quality monolayer graphene on HZO reference (blue), designed to identify the proper combination of laser power and travel rate; the winning combination of 1.243 W and 113 mm/s shows the three characteristic peaks of LIG: The D, G, and 2D peaks at 1360 1580, and 2720 cm^{-1} , respectively. There is a Kapton LIGCP shown in Fig. 4A. B) Optical images of the respective LIGCPs.

For our initial attempt at device making, we prioritized fabrication, assembly, and measurement refinery over rigorously optimizing the design, and experimentally verifying the functionality of, said devices; this task of mathematically/empirically characterizing and optimizing sensor performance is important but was left as a future investigation. Given the explained motive, it should make sense why deciding on a graphene hatching pattern was not a difficult task, so long as the pattern was radial and designed to maximize trace resistance change in response to strain. Much inspiration was taken from the metal patterns of several commercially available circular diaphragm MFSs. To maximize sensor sensitivity, we decided to implement a design which could be read out in a Wheatstone full bridge configuration that allows differential measurements and common mode-suppression from power supply variations and other interfering signals. To enable this option, the pattern features a network of four resistors

consisting of two outer and two inner resistors expected to operate under compressive and tensile stress, respectively. For the purpose of convenience and verification, the four LIG piezoresistors were interconnected in such a way as to allow independent measurements of respective resistances; there were six CI traces printed overall (Fig. 2D).

A. A Cheap Substitute Pressure Sensor which can be Locally and Independently Produced in Under a Day

Whether one is looking for an alternative to traditional MFSs due to their typically long lead and ship times, high cost, untailored offerings, or relatively stagnant improvement, LIG based flexible sensors with simplified PE packaging demonstrate the potential to provide a locally produced, immediate, affordable, custom, and potentially superior alternative with higher sensitivity. Even if one still prefers the precision and reliability of a MFS, the LIG process' ability to quickly substitute (even if only temporarily) the MFS in the event of it being damaged or otherwise rendered defective, remains an irrefutable benefit.

III. CONCEPT AND DEVICE DESIGN

The fundamental figures of merit of a pressure sensor are: (i) the maximum pressure that the membrane can detect and is primarily determined by the yield strength of the membrane material which is roughly 69 MPa for Kapton [10], (ii) pressure measurement repeatability, i.e., after calibrating the piezoresistive sensor—where a function was identified which maps the resistance network state to the correct actual pressure—the mapping should not drift with time or actuations (repeatability is undermined if maximum tolerable pressure is exceeded), (iii) the sensitivity of the device which depends on the sensor material characteristics and device geometry, and (iv) the minimum detectable pressure which sets the sensor resolution and depends on the mechanical and electrical noise from the membrane vibrations and resistive sensors respectively.

A. Design of Pressure Sensor Circular Diaphragm

Before starting the design or fabrication of any pressure sensors, sufficient laser pyrolysis parameters of laser current and writing speed were determined (Fig. 3) from resulting LIG characterization patterns (LIGCPs) (Fig. 4). The resistor network hatch pattern was designed completely parametrically in Fusion 360 and is shown in Fig. 1.

B. Fabrication Process

The first fabrication step (Fig. 2) was to print four sets of three alignment windows per device on a 125 μm thick sheet of Kapton. After loading and aligning the 25.4 μm optics and marked Kapton, the laser carbonized traces were ablated using a VersaLaser VLS3.60 CO_2 laser. A thin rubber gasket with a central (16 mm diameter) diaphragm hole and four outer fastening holes, was also cut using the VersaLaser. Finally, silver leads (partially overlapping the graphene pattern at six points) and blanket insulation layers were deposited using the SV2 printer. An ObJet30 Pro 3D printer made the remaining two components which would form the airtight test chamber (Fig. 5A–B): The top part, having the same profile as the gasket but much thicker, and the bottom part with its four outer fastening holes, underside nut retention slots, female Luer lock input, and

1/8" NPT output. This configuration proves a ready-to-use in-line pressure sensor that allows us to easily swap out various iterations of the membrane device for rapid testing.

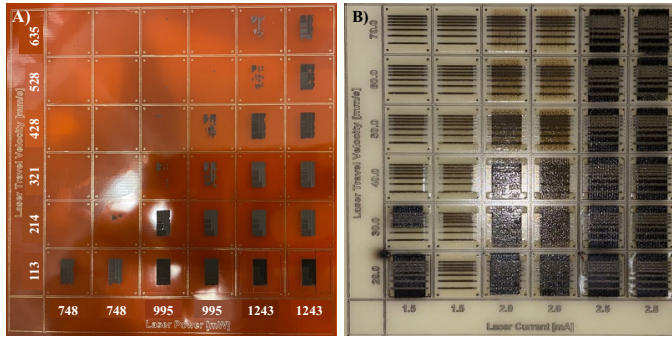


Fig. 4. LIG was defined on **Kapton (A)**, and **FR4 (B)** with SV2 printed CI traces and DI encapsulation shown on FR4 but not on Kapton.

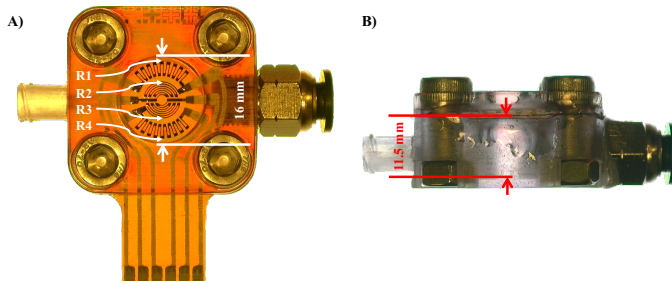


Fig. 5. A) Close-up top view of a fully assembled circular diaphragm pressure sensor with resistor locations. B) Side view of the assembled sensor showing the stack order: Test chamber bottom, gasket, sensor, then test chamber top.

IV. STRESS TESTING AND SENSOR CHARACTERIZATION

The experimental setup is shown in Fig. 6. The reduced volume and increased pressure within the closed pneumatic circuit were induced via syringe pump and measured via pressure sensor, respectively. The DTS-025-02 was used to measure membrane displacement. This data, as well as the resistance data, were recorded for four trials (two in the morning and two at night). Fig. 7 shows the average linear sensitivity was approximately $5 \times 10^{-5} \text{ kPa}^{-1}$ which is comparable to previously achieved sensitivities [1].

V. CONCLUSION AND FURTHER STUDIES

Future work will include FEA optimization of Kapton thickness, piezoresistor lengths, and their locations, for maximum sensitivity with high linearity. The second-generation devices will study the variances in resistances, sensitivities, gauge-factors, and pressure ranges. In summary, this work demonstrated that a high-sensitivity, flexible membrane of strain-gauges can be fabricated, all using PE. This process enables a pathway to allow pressure and piezoresistive accelerometers, force sensors, and gas sensors using graphene multi-sense capabilities with laser-annealing and rapid prototyping cleanroom-less approach.

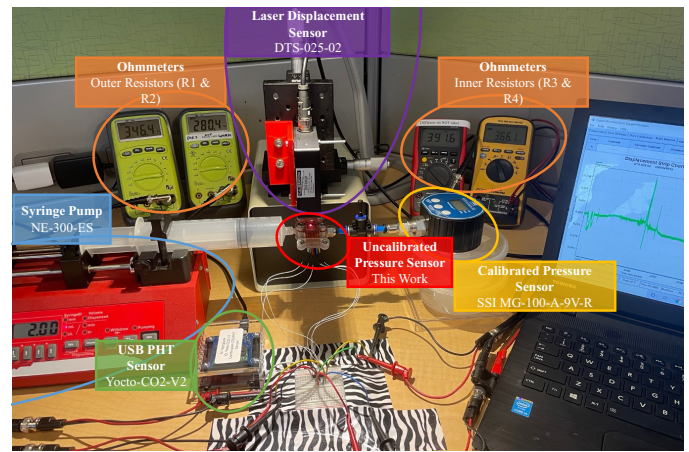


Fig. 6. Experimental setup which produced the data for Fig. 7.

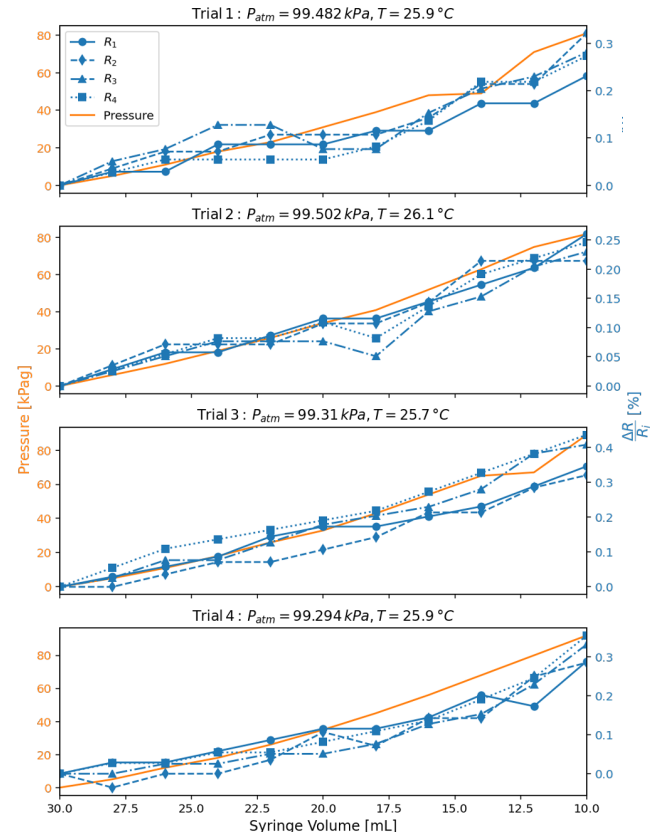


Fig. 7. The percent change in resistance of the four resistors (physical locations specified in Fig. 5A) and the membrane pressure in orange were measured with respect to the reduction of internal volume caused by the syringe pump. From trial 1, at 30 mL, R_1 , R_2 , R_3 , and R_4 were 346.3, 280.3, 391.6, and 366.0 k Ω , resp., while, for the other 3 trials, they varied by $\pm 0.1 \Omega$.

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